CEI section meeting 25-07-2024

Present: David Amorim, Elena de la Fuente Garcia, Dora Gibellieri, Miguel Gonzalez Torre, Erik Kvikne, Christophe Lannoy, Szymon Lopaciuk, Elena Macchia, Lotta Mether, Konstantinos Paraschou, Josephine Potdevin, Giovanni Rumolo, Luca Sabato, Leonardo Sito, Roxana Soos

Online: Chiara Antuono, Gianni Iadarola, Mauro Migliorati, Carlo Zannini

Excused: Xavier Buffat, Lorenzo Giacomel, Fredrik Grønvold, Elias Métral, Nicolas Mounet

Scientific secretary: Roxana Soos

General information (G. Rumolo)

Arising matters

- Future CEI section meetings:
    - **change of time**. Future meetings will start the CEI section meetings at **13:30 on Thursdays** as of September 2024. *This change is done to avoid the overlap with the FCC and HL-LHC TCC meetings*.
    - **change of location**. From January 2025, new location: **6-2-004**.
    - **new content**: Every ~3 month a round table. **1 slide per person**.
- Departures from CEI:
    - Erik Kvikne will end his 11-month technical studentship to go back to Norway to complete his master studies.
    - Elena Macchia will end her 6-month traineeship to go back to Rome and complete her master studies. (*side note: don’t forget to respond to Chiara for the Farewell at Luigia on Wednesday 31 of July*)
- Radiation dosimeter request:
    - New procedure and change of location as of 1 August

  - If you need a dosimeter or wish to request a dosimeter for a third party, whatever the CERN status and the type of dosimeter needed, you need to complete and submit the ServiceNow form online. After your request will be processed, you will be informed that the dosimeter is ready for collection at Building 33 (no longer 55!). The form may also be accessed via the CERN Campus App, under "Campus Life", "Dosimetry".
  - If you already own a dosimeter, you will keep receiving annual email reminders to exchange it, please take the necessary action when you receive these emails.

- Heat waves:
  - There might be heat waves coming in the next couple of weeks
  - Room 6/2-004 air conditioned room has been booked most of the afternoons during the summer and can be used to work there if the office becomes unbearably hot.
  - As a reminder, access to the conference rooms is with your CERN card, which needs to be reactivated once per month at a Lock Activation Card Reader (there is one behind the building 6 cafeteria).

IPP meeting last Friday 19 July

- Discussion on intensity limitation for LHC beam MDs in the injectors following the 930 MHz HOM coupler in cavity 3 on 11 July (Giulia's slides).
  - Breakage did not occur at top intensities seen in the SPS: In fact, when the coupler broke we had not even accelerated 4x 72b to flat top.
  - 23h total downtime beam-to-beam.
  - For caution, a limit to 2e11 proton per bunch has been enforced on LHC beams in the SPS thereafter.
  - This limit strongly impacts LIU ramp-up (potentially 3d next week), HiRadMat run (in two weeks), LHC MDs (in three weeks)
  - We will likely learn more with some visual inspection of other HOMs and EM simulations (*The dynamics of the breakage is not clear yet. Post mortem analysis will be done and will take likely few weeks*)
  - Request to lift the limit has been made and is being evaluated

- AWAKE future plans and beam requests. (*That is a proof of principle of the plasma wake acceleration*)
  - AWAKE takes the beam from the SPS. It is one single LHC-type bunch with higher intensity, accelerated to 450GeV in the SPS and sent to AWAKE.
  - AWAKE (2016 – 2033) will have RUN2c and RUN2d corresponding to the RUN4 of the LHC (between LS3 and LS4). Approved by MTP 2024 (Medium term planning) beside the CNGS dismantling (CERN Neutrinos to Gran Sasso). The cavern currently used by AWAKE was previously used by CNGS, an experiments in which *Neutrinos were produced hitting 400 GeV protons on fixed target, to be then detected at the Gran Sasso laboratroy in Southern Italy and study the oscillations*. The goals of AWAKE runs 2c and 2d are:
    - Accelerate an electron beam to high energies (gradient of 0.5-1GV/m)
    - Control the electron beam quality (~10 mm-mrad emittance, 10% energy spread)
    - Demonstrate scalable plasma source technology
  - Post-LS4: Hopefully a particle physics case will be developed for first application of the AWAKE-like technology
  - AWAKE beam requests:
    - 12 weeks per year, in blocks of 2-3 weeks, separated by several weeks (2/3 shifts)
    - More than 1400 extractions/day (same target today, but rarely achieved)
    - Shorter proton bunch length: 1 sigma ~ 100 ps (now 175 ps)
    - More protons: 0.5 – 4e11 protons/bunch (now 0.5 – 3e11 protons/bunch)
    - Shorter cycle? 6 s cycle length
    - Stable beam conditions for several hours, no interruptions!
  - AWAKE beam status in the injectors
    - Longitudinal instability at PS transition crossing prevents reaching 4e11 protons per bunch with the target longitudinal emittance of 0.35 eVs, which wuld allow obtaining the desired bunch length at SPS extraction.
    - Reducing longitudinal impedance in PS (shielding of pumping ports) is expected to alleviate this limitation
    - In the SPS the lowest theoretically achievable bunch length for 4e11 is 0.5 ns, compatibly with post-LS3 AWAKE requests.

2024 injectors v2.1

- Next week 3 full days for dedicated MDs in the SPS due to NA intervention for magnet exchange
    - No extraction to North Area possible, so users will basically be COLDEX and LIU ramp-up. *Keeping the limitation at 2e11 proton per bunch would be missing a great opportunity*
    - Wire Scanner 51638H stuck (37H operational) at 2.3 rad. *Fortunately not directly in beam however grazing beam halo and closing loop around beam, more info in Elena's slides in AOB*
        - Large heating observed
        - Eventually the wire got burnt during the Q22 cycle set-up
        - Impedance in this position shows that a large power is dissipated on the wire, reaching potentially damaging values for large beam intensity and not specially short bunches – thanks Elena and Leo for the quick feedback!
        - Indeed the power loss, already close to threshold for wire burning with LHC OP beam (3x 36b, 1.6e11 proton per bunch, 1.55 ns), became intolerable with 4x 72b 1.8e11 proton per bunch, >2 ns → Wire burnt Tuesday night.

2024 LHC schedule v2.0

- Physics production with still increasing availability, which leads us closer to the target integrated luminosity curve.
- LHC integrated luminosity still falling behind target by few days, seemed to be recovering with high availability till 24/07 morning, then almost 24h passed without beam on access and miscellaneous problems (PSB, QPS intervention in sector 23)

LHC beam parameters

- New brighter variant of BCMS planned to be taken before the weekend. *We might see improvements on the emittances* Heat load stuck in between 160 and 165 W/Half-cell.

Giovanni asks Lotta if there is a possibility to put more bunches with different filling scheme. **Lotta** answers that there is not much to be gained. The only thing that can be considered is to go to trains with 4x36 or 5x36 (~20W/hc more), but it is not possible to switch to longer trains (48b trains).

Beam coupling impedance of resonant cavities in non-ultrarelativistic regime (E. Macchia):

Introduction

Beam coupling impedance

- The beam coupling impedance describes the interaction of a particle beam with the surrounding environment.
- For a device of length l, the beam coupling impedance is defined as:

$$Z_{//} = -\frac{1}{q_0} \int_0^l E_s e^{jks} ds$$

$$Z_{x,y} = \frac{j}{q_0} \int_0^l \left[E_{x,y} - \beta Z_0 H_{x,y} \right] e^{jks} ds$$

with $E_{s,x,y}$ and $H_{x,y}$ electric and magnetic induced fields in the frequency domain.

- This is the definition used by CST and wakis, but other definitions are possible, and they can include the normalization to the particle velocity (Sacherer definition).

Space charge effects

- When $\boldsymbol{\beta} < \mathbf{1}$, the charged particles of a beam also create self-fields, that lead to space charge effects
  - direct space charge (DSC): interaction of the particles among each other in open space.
  - indirect space charge (ISC): interaction of the particles among each other due to the external environment (*e.g., perfectly conducting walls*)

- While indirect space charge is typically taken into account directly in the impedance model, the direct space charge impedance has to be removed.

Electromagnetic simulations for non-ultrarelativistic beams

- For ultrarelativistic beams, the reliability of CST has been extensively proved.
- But CST can't discriminate between the fields induced by the beam, so the simulated beam coupling impedance of a device under test (DUT) is $Z^{tot}(\beta) = Z(\beta) + Z^{SC}(\beta)$, where
  - $Z(\beta)$ is the DUT's impedance, which includes the indirect space charge impedance.

  - $Z^{SC}(\beta)$ is the direct space charge impedance.
- For **β = $\mathbf{1}$** it results $Z^{SC}(\beta) = 0$.
- For non-ultrarelativistic beams, the main complication consists in removing the contribution of the direct space charge of the source bunch.

Simulations of the bounding box

- CST simulations take place within a delimited domain called bounding box. *Since CST is a numerical solver, it discretizes the domain with a mesh grid.*
- The bounding box (bb) can be simulated without changing its discretization, by excluding all the elements of the DUT from the simulation.
- The resulting beam coupling impedance can be written as $Z_{bb}^{tot}(\beta) = Z_{bb}^{ISC}(\beta) + Z^{SC}(\beta)$, where $Z_{bb}^{ISC}(\beta)$ is the indirect space charge impedance of the bounding box.

Numerical cancellation of $\boldsymbol{Z^{SC}(\beta)}$

- Two simulations are run with the same mesh:
  - Simulation of the device under test: $Z^{tot}(\beta) = Z(\beta) + Z^{SC}(\beta)$
  - Simulation of the bounding box: $Z_{bb}^{tot}(\beta) = Z_{bb}^{ISC}(\beta) + Z^{SC}(\beta)$

$$Z^{tot}(\beta) - Z_{bb}^{tot}(\beta) = Z(\beta) - Z_{bb}^{ISC}(\beta)$$

- $Z_{bb}^{ISC}(\beta)$ can be analytically calculated and removed.
- This technique can also be applied directly to the wake potential.
- Examples of applications can be found in the presentation done during the ABP-CEI Section Meeting of 16 May 2024.

Simulations of a pillbox cavity

Study of the behavior of the quality factor with β

Pillbox cavity

Study of the first resonant mode: TM_{010} in the pillbox cavity.

Eigenmode Solver vs Wakefield Solver

- Wakefield Solver (WF): directly provides the impedance spectrum.
- Eigenmode Solver (EM): provides three parameters. *impedance spectrum*

reconstructed based on the broad-band resonator model.

broad-band resonator model:

$$Z(\omega) = \frac{R_s}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

Longitudinal peak impedance varying β

- Parametric study of the real part of the impedance at f_{010} varying β.
- Good agreement between the two solvers: *Relative error < 5%*
- This agreement was not obvious because in the EM solver the particle velocity is taken into account only in post-processing.

Quality factor varying β: computation from the real part of the longitudinal impedance

The quality factor of the beam coupling impedance can be computed from its real part or from its magnitude.

- Eigenmode solver: Q is constant with β.
- Q computed from the real part: good agreement between the two solvers.
- Q computed from the magnitude: lower values.

Wakefield solver: impedance spectrum varying β

Indirect space charge is still present and affects the imaginary part of the impedance, thus altering its magnitude.

Impedance spectrum comparison: β=0.9

ISC is low: agreement between the two solvers.

Impedance spectrum comparison: β=0.7

ISC is higher, the shape of the magnitude's curve is corrupted. We can ask ourselves if Q computed from the magnitude is still meaningful.

Simulations of the PSB's FINEMET cavities

Model and challenges

The PSB's FINEMET cavities

Study on the FINEMET cavities' realistic 3D model, imported from CATIA and simplified for electromagnetic simulations.

Inside the metallic box of one cavity there is 6 cells with a copper ring and a FINEMET ring. One cell: vacuum chamber with ceramic gap at the center and a FINEMET ring on either side.

2 cavities in each accelerating station, 3 accelerating stations in each of the 4 rings of the PSB.

Challenges

- To have convergence of the results: ≅ 60 million mesh cells
- For $\beta = 1$: total simulation time ≅ 3 hours
- For $\beta < 1$ the simulations of the bounding box are very long → first to be tried. In fact CST throws an error message stating that it is unable to solve the electrostatic problem for the interface region because of memory issues (*even on HPCs with very hogh RAM*). Solutions are however proposed in the CST documenation from which two are realistic to try:
  - Relax the mesh to increas the maximum stable timestep of the wakefield simulation.
  - Increase the maximum number of allowed points with the VBA command: Solver.MaxPointsBeamInterfaceCalc "XXX".

Elena de la Fuente Garcia *will later ask about this problem:*
In CST, if the beta was chosen to be less than 0.999 a full 3D electrostatic problem must be solved before the wake-simulation is started, this means considering the eigenfield of the moving charge at the boundaries. This is extremely time and memory consuming. The program will usually crash at the first bounday condition before the begining of the simulation. ***Elena*** *thinks that this might be to give the initial conditions on the fields, when the charge is at a certain position in the begining one solves the Poisson's equation. Like this thes may correct the perturbation that one creates when injecting the beam.*

Solutions

- Number of allowed mesh points increased → simulation runs but then stops again: "Memory allocation failed", even on high-capacity RAM computers.

- Model simplified → removal of negligible parts and simpler beam pipe: ≅ 50 million cells (*10 million cells less, but still too heavy*).
- Final solution: 2 cells model → 7÷16 million cells depending on β.

Impedance: results

Longitudinal impedance: β=1 vs β=0.7

The shape of the imaginary part for $\boldsymbol{\beta = 0.7}$ is due to the presence of the ISC.
For the simplified beam pipe:

$$Z_{//}\left(\omega\right) = \frac{j\omega\mu_0 L}{2\pi\beta^2\gamma^2}\frac{K_0\left(\frac{kb}{\gamma}\right)}{I_0\left(\frac{kb}{\gamma}\right)}$$

Transverse horizontal dipolar impedance: β=1 vs β=0.7

The higher value of the imaginary part for $\boldsymbol{\beta = 0.7}$ is due to the presence of the ISC.
For the simplified beam pipe:

$$Z_{\perp}\left(\omega\right) = \frac{jk^2 Z_0 L}{4\pi\beta\gamma^4}\frac{K_1\left(\frac{kb}{\gamma}\right)}{I_1\left(\frac{kb}{\gamma}\right)}$$

Transverse horizontal quadrupolar impedance: β=1 vs β=0.7

- For $\beta = 1$, $Z^{quad} \cong 0$ because there is almost a circular symmetry.
- For $\boldsymbol{\beta < 1}$ there is a radial field dependence: Im{Z^{quad}} gets higher.

Transverse vertical dipolar impedance: β=1 vs β=0.7

- As before, the higher value of the imaginary part for $\boldsymbol{\beta = 0.7}$ is due to the presence of the ISC.

Transverse vertical quadrupolar impedance: β=1 vs β=0.7

- For $\beta = 1$, $Z^{quad} \cong 0$ because there is almost a circular symmetry.
- For $\boldsymbol{\beta < 1}$ there is a radial field dependence: Im{Z^{quad}} gets higher.

Simulations of a cubic cavity with wakis

Use of wakis

Use of wakis: cubic cavity

A script exemple is displayed, with a comment from Elena M. that the wakis ‘interface’ is very easy to use and that she thanks Elena dlFG for her extensive help.

Wake potential and impedance magnitude

Wake potential and |Z|: β=1
For $\beta = 1$ there is good agreement between CST and wakis.

Wake potential and |Z| varying β: β=0.9
As β decreases, there is still good agreement between the two solvers.

Wake potential and |Z| varying β: β=0.7 / β=0.5
As β decreases, there is still good agreement between the two solvers. From the wake potential, we can notice that CST injects the beam after or slower.

Real and imaginary parts of the impedance

Real and imaginary parts of Z varying β: β=0.9/ β=0.7 / β=0.5
As β decreases, the real parts of Z in the two solvers start to drift apart.

Possible solution: adjustment of the deconvolution algorithm in wakis to account for $\beta < 1$.

$$Z_{//}(\omega) = -\frac{\int_{-\infty}^{\infty} W_{//}(s)\, e^{-j\omega s} ds}{\int_{-\infty}^{\infty} \beta c \lambda(s)\, e^{-j\omega s} ds}$$

Numerical cancellation of DSC on Re($Z_{//}$) for β=0.5

- Performing the numerical cancellation of the DSC on both, the two curves appear to get closer.
- The presence of resonances in wakis is due to the fact that PML boundary conditions are still under development. (*PEC was used instead: the bounding box acts as a resonator*)

Conclusions

- Low-beta simulations are extremely challenging due to a series of factors (mesh convergence, direct integration method, removal of direct space charge, etc.).

- The numerical cancellation technique for the removal of the DSC contribution was benchmarked with a resistive wall beam chamber:
  - $Z_{||}$ doesn't change with **β**, as expected;
  - $Z_{\perp}$ scales with **β**, as expected.
- Simulations of a pillbox cavity:
  - Good agreement between the peak impedance computed with the EM Solver and the WF Solver:
    - The non-ultrarelativistic WF simulations are accurate.
    - The EM Solver approximation of adding particle velocity only in post-processing with the transit time factor has been found to be accurate.
  - Comparison between the quality factor computed with the EM Solver and the WF Solver:
    - Good agreement when Q is computed from the real part of the impedance;
    - Computation of Q from the magnitude is energy-dependent due to the impact of ISC. Is it still meaningful?
- Low-beta simulations of complex structures like the FINEMET cavities are extremely demanding due to computational challenges posed by the simulations of the DSC.
  - For $\beta = 1$, the simulation of the 6-cell model is~3 hours long.
  - For $\beta = 0.7$, the simulations of the simplified 2-cell model are~3 hours long and the simulations of the bounding box are~24 ÷ 28 hours long.
- While the real part has a similar amplitude and behavior, the imaginary part of the impedance when $\beta < 1$ show higher values with respect to the results for $\beta = 1$, consistently with the presence of indirect space charge.
- Wakisis easy to use after a brief introduction.
  - Despite the lack of time, it was possible to conduct a full analysis varying β.
- It was possible to confirm that wakis simulations correctly follow the behavior of the impedance
  with β.
- Differences are visible disentangling real and imaginary parts.
  - Investigations ongoing with wakis.

Next steps

- Simulations on the FINEMET cavities at different energies are running.
- Assessment of the impact of the non-ultrarelativistic FINEMET impedance model on the total PSB impedance.

  - Impact on the coherent tune shift vs chromaticity.
  - Consistency of the model with tune shift measurements.
  - Impact on instability growth rate and benchmark with measurements could also be performed.
- Tailored studies to optimize low-beta simulations in wakis.

Remarks:

Elena dlF.G. comments that she is extremely happy about these results as the previous year there was yet no line of code written, and now there is a user, the β begaviour, etc… Learning about some issues was a good insight to what is also in CST that is a black box for us. This sort of studies always gives light to how things may work.

Dora G. asks how one could include the effects of the indirect space charge. The response was that we include it because in the simulations the indirect space charge is present, and one does not try to remove it, in fact we cannot remove it in real life. We just take the results of the simulation and remove the direct space charge and consider the fact that there is indirect space charge. **Giovanni** ads that it is a correct as the indirect sapce charge is part of the impedance.

A second question from **Dora** was about the physical reason of why you only see an effect on the imaginary part. This is why ideally space charge should only be an imaginary contribution of the impedance as it is only responsible for losses.

Carlo comments also that if one considers only the direct space charge, with a simple assumption on the low frequencies it will just be a dirac delta, but in reality it is something else that is symmetric with a bandwith in the transverse plane.

David was wondering why for the Pillbox cavity, the impedance spectrum for different betas has an odd shape and it is not monotonic. **Elena** answeres that it is because it follows the peak impedance, see slide 13. Because when the peak impedance has a higher real part, and the imaginary part gets lower, it gets insignificant.

Kostas wanted to know if the only problem with this procedure was to simulate the bounding box indirect space charge. In **Elena**’s opinion, it appears so, but after simulation of the bounding box, the results are pretty good. One had exactly the expected result. The indirect space charge can be removed analytically but the direct can’t. For a complex sturcture there is a lot of numerical noise so it can be tricky to do the simulations in fact. **Kostas** wondered further is there was an analytical method to compute the indirect space charge of the bounding box. **Carlo** tried to do this but the problem is that the accuracy compromises the results of the simulation because there is too much noise.

Finally **Carlo** thanks Elena for her incredible work in such a short time, it was very challanging. It came from these studies that you can put particle velocity in the post processing. This simplifies things when studying resonnances. And thanks to Chiara for supervising.

Wrap-up on Eddy Current Effects in the NC RCS Vacuum Chamber (E. Kvikne):

Introduction

- High energy complex of the Muon collider consists of a chain of Rapid Cycling Synchrotrons (RCS)
- Goal:
  – Accelerate muon from 63 GeV to 5 TeV.
  – This acceleration must occur within approximately 10 ms to ensure a muon survival rate of at least 65%.
- The magnetic field strength must ramp with the muons' energy, causing rapid changes of the
  magnetic field.
- These rapid changes induce Eddy currents within conductive materials, leading to both field distortions and power losses.
- This study aims to understand the magnitude of the eddy currents generated under extreme ramp conditions and explore vacuum chamber designs that both minimizes these undesirable effects while keeping beam coupling impedance low.

Eddy Currents in Vacuum Chamber of Fast Ramping NC Magnets

- The ohmic loss per unit length due to eddy currents in two different designs was investigated
- By assuming a uniform, time-varying magnetic field the ohmic loss per unit length can be derived analytically under certain additional conditions.

$$P_{\mathrm{rect}}/L = \frac{\dot{B}^2 a^2 d\sigma}{2}\left(\frac{a}{3} + b\right)$$

$$P_{\mathrm{striped}}/L = \frac{\dot{B}^2 \omega d\sigma}{3}\left(\frac{N_H \omega^2}{4} + N_V d^2\right)$$

Electromagnetic simulation

- Uncertainties arise regarding the analytical formula’s applicability due to the rapid ramp rates of the RCS.
- Ansys Maxwell2D was used to validate the analytical formula by comparing with electromagnetic simulations for conditions similar to the ones of the RCS.
- In these simulations a uniform magnetic field is created between two large conducting plates, excited by an alternating current with frequency f. The field strength at any point is approximately given by: $B\left(t\right) = B_0 \cos\left(2\pi f.\, t\right)$

Stainless Steel Rectangular Vacuum Chamber

Stainless steel:

- Conductivity: 1.1 × 106 S/m
- Height and width: 30X100mm
- Thickness: 0.3mm

Longitudinal striped design

By changing to a striped design, while keeping the thickness unchanged, we see a reduction of ohmic loss of 2-3 orders of magnitude depending on the width of the stripes.

This assumes the parallel stripes to be touching. In reality we would have some spacing between them. This will in turn reduce the number of stripes and thus the ohmic loss further.

Example from J-PARC

In J-PARC they use ceramic vacuum chambers because of it’s low conductivity. There are some copper stripes that are thin enough so that the Eddy currents would not be significant. But design won’t work for the Muon Collider (MC) as at J-PARC they are using maximum 70 T/s compared to de design of MC that is 4200 T/s. It is still a good show case of the technology to reduce Eddy currents.

Giovanni asks if the Eddy currents are mostly longitudinal and not transverse. They are in fact longitudinal. That's why the strip design works while maintaining the current flow.

Impedance and Wakes

Vacuum Chamber Impedance

- The vacuum chamber is expected to be a large contributor to the total impedance of each RCS because …
  – The NC sections makes up between 41% and 61% of each RCS and
  – The magnet aperture is quite small at 30x100mm and it needs to house both the ceramic layer (~5mm) and RF shield.
- The impedance of two different simplified vacuum chambers was computed using IW2D.
- The vacuum chambers was assumed to be circular and the RF shield was modeled as a uniform layer*.

RF-Shield Outside Ceramic

- Changing the copper thickness has an impact on the lower frequency region of the impedance.
- However there are resonances caused by the ceramic that remains unaffected by the change in copper thickness.
- The impedance of these resonances are orders of magnitudes larger than the resistive-wall impedance we get without the ceramic layer

Comparison of Beam Pipe and Cavity Impedance for RCS2

- RCS2 Specifications:
  – Beam pipe length: 2539 m (NC magnet length)
  – Number of cavities: 374
- The resonances caused by the ceramic are significantly larger than the ones from the cavities.
- David has shown that the impedance from the cavities is already close to the instability threshold in the 4 RCS chain simulation.
- Given that the resonances from the beam pipe are ~10x greater than those from the

cavities, a stable beam is not achievable with this design.

RCS2 Cavity and Beam Pipe Wake

- The wake was computed from the impedance in order to run XSuite simulations.
- As expected from the impedance plot, the beam pipe wake is significantly larger than the cavity wake.
- Changes in the copper thickness have little impact on the beam pipe wake due to the dominance of the ceramic resonances.
- The full RCS chain XSuite simulations showed, consistent with our expectations, that all the particles were lost within the first two RCS.

RF-Shield Inside Ceramic

- Even with a very thin (~nm) layer of copper we are able to suppress the resonances we saw in Design 1.
  – This effect is explained by Zotter on page 168 in “Impedances and Wakes in High Energy Particle Accelerators”

- Increasing the thickness of the copper layer can significantly reduce the impedance at higher frequencies.

- The wake has a strong dependence on the thickness of the copper layer. By decreasing the copper thickness, we see an increase in the wake magnitude.

- By setting the copper thickness to zero, we are essentially left with Design 1 with an infinitely thick copper layer.

- To determine the thickness of copper needed to provide sufficient RF-shielding to the beam, we will conduct full RCS chain simulations using XSuite.

Radius and Thickness scan

The impedance was also computed for a number of different inner radii and RF shield thicknesses, which was later used to study beam dynamic with XSuite.

XSuite stability simulations

XSuite Simulation Parameters and Setup

D.Amorim's presentation at the 2024 IMCC and MuCol Annual Meeting details the general setup for start-to end XSuite simulation of the RCS chain.

Simulations were conducted scanning over different chromaticities, horizontal damper strengths and initial offsets at the entrance of an RCS, focusing on analyzing the wake effects of the Design 2 beam pipe at different copper thicknesses.

Some machine parameters are presented.

Result Plots of XSuite Simulation

The result of the simulations are presented as heat maps

The color intensity on these maps represents the normalized horizontal emittance growth between the beginning of RCS1 and end of RCS4.

The x-axis represents the initial transverse offset at the entrance of each RCS

The y-axis indicates the damping time, measured in number of turns.

The plot title includes the chromaticity and an impedance scaling factor.

Bunch Stability at Varying Inner Radius

The stability at different inner radii was investigated with a 10µm titanium layer and 5 mm ceramic layer.

Simulations where the particle loss was larger than 10% are marked in red, showing that stable beam is not achievable with a inner radius of 5mm.

At 7.5mm we see no emittance growth at an initial offset of 10µm or less.

While we allow for a larger offset with an inner radius of 10mm.

Bunch Stability at Varying Titanium Thickness

With a 6µm Titanium layer the beam is stable for all non-negative Q′, as long as the offset is smaller than 1000µm.

A slight improvement can be observed when increasing the Titanium thickness to 10µm.

After 10µm we see no additional improvements of the stability.

Instabilities in RCS4

Many of the observed instabilities develop in RCS4, primarily due to its longer sections of NC magnets.

Having a thicker layer of shielding within RCS4 could help mitigate some of these instabilities.

Conclusions

- Minimize Conductive Materials:
  – The RCS vacuum chamber should limit conductive material to reduce eddy current flow.
- Ceramic With Metallic Stripes:
  – Ceramic is effective but requires conductive stripes to maintain low impedance.
  – Segmenting metal into thin longitudinal stripes significantly lowers eddy currents.
  – The stripes should be placed internally to suppress resonances seen with external coatings.
- Further study:
  - Further investigation needed on the dimensions and spacing of stripes to manage heat effectively

Titanium Ceramic Chamber:

- Inner Radius Challenges:
  – For a ceramic vacuum chamber with titanium coating a 7.5mm radius allows for stable beam.
  – With a radius of 10mm we see stability over a broader range of offsets and damper strengths.
- Titanium Layer thickness:
  – Critical for stability.
  – 6 µm sufficient for stable beam across various settings.
  – No stability improvement with thickness beyond 10 µm.
- Further study:
  – Combine impedance from vacuum chamber with other impedance sources into a unified RCS impedance model.

Remarks

David would like to thank Erik as with his work the Muon Collider wnet from no vacuum chamber design in the RCS at all to know already about some problems they may have, knowing more what is needed from the impedance side.

Giovanni wonders if considering the stripes have an impact on the impedance model compared to the continuous layer. Apparently both are equivalent from the impedance point of view. This study was already done for RF systems.

This won't be the subject of Erik's master thesis.

End of the meeting

By lack of energy the last presentation in AOB has been postponed to the coffee break afterwards.